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Prioritization of sub-watershed in Eastern Jeddah using PCA-WSA hybrid modeling approach

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Abstract

The development and implementation of any watershed management plan require a thorough understanding of geometrical circumstances within the watershed. Therefore, watershed planning and management as well as the delineation of natural drainage systems are carried out by the application of GIS-based morphometric analysis. The current work proposes a hybrid model that incorporates multivariate statistical models and geo-informatics to determine the most significant erosion-prone morphometric characteristics and sub-watersheds for the eastern Jeddah sub-watersheds. In recent decades, the Eastern Jeddah sub watershed has suffered multiple catastrophic floods and soil erosions, resulting in numerous fatalities, wrecked homes, and badly damaged vehicles. Principal component analysis (PCA) and Weighted Sum Approach (WSA), two statistical approaches, are coupled to determine the Jeddah Eastern Sub-Watersheds (SWDs) that need to be managed for soil conservation. The relevant correlated factor-loading matrix was identified using PCA, and the weights for the morphometric parameters were provided using WSA, which also established their priority ranking for classification according to compound factor value. The most vulnerable sub-watersheds are SWD-9 and SWD-11, and the results indicated that very sensitive zone sub-watersheds make up 56.48% of the entire region. This emphasizes the need for appropriate conservation measures for water and soil to be implemented by the Jeddah water authorities. In terms of estimating the risk of erosion, the suggested methodology turned out to be a useful management and planning tool for watershed priotization. It has been demonstrated that using PCA and WSA together is a useful technique for enhancing long-term soil erosion prevention strategies and watershed conservation priorities.

Keywords Jeddah · Morphometric parameters · Priotrization · Principal component · Weighted sum approach

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1 Introduction

Watershed management refers to the process of managing a section of land that ends at a specific location next to a river or other watercourse in order to preserve ecological assets, including land and water (Tomer, 2014). The management of watersheds is becoming more crucial in conservation planning due to the variety of human and natural processes that cause the resources in the watershed to degrade. According to global statistics, various degradation processes impact over 50% of agricultural lands globally, with water erosion accounting for nearly 80% of these impacts (Kumawat et al., 2021). Additionally, as aquifers continue to run dry and underground water needs rise daily, the world's food production systems are put in jeopardy. This has led to major global climate problems such as desertification, drought, and land subsidence (Chitsazan et al., 2020). The degradation of watershed resources is causing a danger to worldwide sustained economic growth and a decline in environmental quality. Similar to other nations globally, Saudi Arabia is confronted with a range of water and soil erosion challenges, including erosion and runoff from flooding on streets (Rahaman et al., 2016). To create a strategy for preserving water and soil in given watersheds, researchers must thus determine the most vulnerable zones due to the impending threat of catastrophic water and land degradation (Kabir & Hossen, 2019).

During floods, a significant volume of sediment transport from the eastern Jeddah Watersheds is transported to the southern region of Jeddah (Al-Juaidi, 2020; Al-Juaidi, 2023; Youssef et al., 2016). Because of this, during the rainy season, roadway erosion is a typical problem. Because of the excessive rainfall, erosion, and sediments, the area has had to deal with multiple watershed-related catastrophes, which have destroyed homes and cars and killed people (Youssef et al., 2016).

In 2009, 2011, 2021, and 2022, three successive flash floods impacted the Eastern Jeddah Sub-watersheds. According to Youssef et al. (2016), the extremist flash floods occurred in 2009. The city's damages during the 2009 flood are thought to have cost it USD 2.6 billion, 113 people died, 10,000 homes were destroyed, and 17,000 vehicles were severely damaged in the flood of 2009. Furthermore, severe soil erosion was induced by these storms across the watersheds (, 2023; Dano, 2020; Youssef et al., 2016). The 2009 disastrous floods, which took numerous lives and destroyed a large number of dwellings, were largely caused by the sixteen sub-watersheds. According to Al Saud (2015), Jeddah has put into practice a number of flash flood mitigation methods, such as (a) large-scale ponds, stormwater drainage systems, and cleaning plans for open channels that are already existing at the exits of watersheds. To divert stormwater away from watershed outlets and onto these open channels. The objective of these open channels is to divert runoff away from watershed outlets and toward the Red Sea (Youssef et al., 2016).

The Saudi Arabian water authorities aim to put into practice a strategy that includes watershed management and quick response to instances of flooding (Al-juaidi et al., 2010; Al-juaidi, 2019a, 2019b, 2023; Al-juaidi et al. 2018; Al-Shutayri & Al-juaidi, 2019). The threat of flooding in Eastern Jeddah will therefore be reduced by identifying the sub-watershed that reacts to flooding more quickly. By selecting the sub-watershed that is most prone to flooding, precious time can be saved for effective watershed planning, design, and implementation.

In these circumstances, the practice of watershed prioritization must be used to prioritize the management of the available natural resources by focusing on the risk zone within the watershed. Consequently, choosing sub-watersheds for a detailed geomorphometric study requires careful thought. Evaluating the linear, aerial, and shape features of the topographic configuration in relation to the drainage basin describes the geo-morphometric analysis (Aher et al., 2014). A watershed's morphometric analysis provides a quantitative assessment of its geometry and natural drainage system, both of which are crucial elements in the delineation of a watershed (Horton, 1945; Strahler, 1964). Prioritizing sub-watersheds is thought to be most typically accomplished by the application of geo-morphometric analysis (Biswas et al., 1999; Aher et al., 2014).

The best method for analyzing a watershed is through geo-informatics and morphometric analysis. The application of Geospatial Information Systems (GIS) to deal with the nature and structure of spatial data as well as its gathering, classification, and organization is known as geo-informatics (Aher et al., 2014; , 2018; Al-Juaidi et al., 2011, 2014, 2018). For morphometric analysis, it is not required to fully comprehend the relationships between the various drainage pattern components of the watershed. Morphometric analysis makes it feasible to compare several watersheds produced under various geology and climatic regimes (Prabhakaran & Raj, 2018).

In order to effectively manage and plan for natural resources, morphometric analysis is essential for prioritizing sub-watersheds. The network of drainage channels inside a watershed is the main focus of linear parameters. They offer details on the channel geometry, connection, and flow pathways. These linear parameters assist us in identifying key locations vulnerable to erosion, sediment deposition, or floods as well as the hydrological behavior of the watershed. The dimensions and forms of the landforms inside a watershed are described by the areal and shape parameters. They comprise characteristics of land features' area, shape, and distribution. By analyzing these areal and shape parameters, one can learn more about the geometric characteristics of the land that affect water flow, erosion, and sediment movement (Kumar et al., 2021).

A complete strategy for prioritizing sub-watersheds that promotes sustainable resource consumption and watershed management is made possible by the integration of areal shape and linear characteristics. Rank sub-watersheds according to how vulnerable they are to runoff, soil erosion, and other environmental factors by incorporating both areal shape and linear metrics (Malik et al., 2019).

The sub-watersheds can be rated according to how susceptible they are to runoff, soil erosion, and other environmental issues by incorporating all linear areal and shape metrics. For example, sub-watersheds that include a lot of streams, lengthy forms, and big basin areas, could be more prone to erosion. Setting priorities enables decision-makers to focus on the most important areas for soil and water conservation techniques, allowing them to deploy resources effectively. By taking into account all important factors, methods such as weighted sum analysis assist in determining the most important priority (Aher et al., 2014; Al-Juaidi, 2024).

Prioritizing sub-watersheds for efficient planning and management of natural resources depend significantly on morphometric analysis. By analyzing areal and shape parameters, we gain insights into the geometric characteristics of the landscape, which influence water flow, erosion, and sediment transport (Nitheshnirmal et al., 2019; Sutradhar, 2020). Linear parameters focus on the network of drainage channels within a watershed. The linear parameters provide information about the flow paths, connectivity, and channel geometry (Kumar et al., 2018; Sutradhar, 2020). These characteristics assist in our comprehension of the watershed's hydrological behavior and help us identify crucial areas vulnerable to flooding, erosion, and sediment deposition (Al-Juaidi & Attia, 2020; Kandpal et al., 2017; Mangan et al., 2019).

By combining both areal shape and linear parameters, we can rank sub-watersheds based on their vulnerability to soil erosion, runoff, and other environmental factors. For instance, sub-watersheds with high stream density, elongated shapes, and large basin areas may be more susceptible to erosion. Prioritization allows decision-makers to allocate resources effectively, focusing on the most critical areas for soil and water conservation practices. Techniques like weighted sum analysis help determine the final priority, considering all relevant parameters. The integration of areal shape and linear parameters provides a comprehensive approach to prioritize sub-watersheds, leading to sustainable watershed management and resource utilization.

Establishing subwatersheds as a top priority protects, restores, and promotes a long-term preservation of the region's terrestrial ecosystems—all of which are essential components of successful watershed conservation. The earth's surface, the shape and size of its landforms at different regional scales, and a range of hydrological, topographic, and areal elements are all included in the morphometric investigation of observations and quantitative evaluation (Aher et al., 2014).

Following Schumm (1956) and Strahler (1964), set the groundwork for a quantitative investigation of basin morphometry. According to numerous researchers, this aids in monitoring soil erosion and promoting the sustainable development of sub-watersheds that are critically endangered (Arefin et al., 2020). Geomorphometric multivariate analysis has been used in many research to identify sub-watersheds at various scales (Adhami & Sadeghi, 2016; Farhan et al., 2018; Meshram & Sharma, 2018; Malik et al., 2019). Recently, watersheds have been prioritized based on morphometric parameters using principal component analysis (PCA) and weighted-sum analysis (WSA) (Aher et al., 2014; Kadam et al., 2017, 2019; Kandpal et al., 2018; Kumar et al., 2021; Malik et al., 2019; Rahman et al., 2021; Sahu et al., 2018; Shekar & Mathew, 2022; Singh & Singh, 2018).

According to earlier research, the SWD prioritization process used compound factor values, which are determined by arithmetically averaging the preliminary priority ranks to determine the ultimate SWD priority. Prior techniques assigned each morphometric parameter the same weight, which may not be the case in practice (Aher et al., 2014; Singh & Singh, 2018). Every SWD is unique, thus when selecting places that are extremely sensitive for risk evaluation and control, the value of each input constraint might not be the same (Meshram et al., 2018; Kadam et al., 2019).

An optimistic approach to SWD prioritization was indicated by the recent hybridization of the PCA and WSA. As a consequence, the goal of the current work is to use morphometric metrics to rank sixteen mountainous SWD of the Eastern Jeddah. The following morphological parameters are used to determine the demonstrating procedure: (i) linear: texture ratio, drainage density, mean length of overland flow, bifurcation ratio, and stream order; (ii) areal: texture ratio, form factor, circularity ratio, and elongation ratio; and (iii) shape: compactness coefficient, form factor, circularity ratio, and elongation ratio. This work was completed in two steps using GIS techniques: (i) calculating the sub-watersheds' morphometric parameters east of Jeddah city; and (ii) employing the weighted sum approach (WSA) and principal component analysis (PCA) together to find the sub-watersheds, classifying and ranking them for conservation management and planning. The combination of PCA and WSA recently provided a promising approach for SWD prioritizing. Thus, the major goal is to use morphometric criteria to rank Jeddah's sixteen sub-watersheds (SWDs). This work is extremely critical for the sub-watersheds in eastern Jeddah, where reliable watershed management and sustainability are essential. By providing a sound method for SWD prioritization, this work will help with various aspects of Jeddah's water resource management, including soil erosion and flood control. The primary goal of this investigation was to contribute to several water resource engineering fields by providing a stable method for SWD priority in eastern Jeddah. This is vital for a place like this, where reliable governance of watersheds and sustainable development are essential.

2 Materials and methods

The steps of the methodology are as follows: (1) Description of the Eastern Jeddah sub-watersheds where flooding and soil erosions are possible due to flash strong rainfalls. (2) GIS spatial analyst software is used to identify the drainage system and sub-watersheds. In order to identify the stream and watersheds in this investigation, a 30 m × 30 m resolution digital elevation model (DEM) was employed (https://earthexplorer.usgs.gov). (3) Identify the sub watersheds' linear, areal, and form morphological properties. (4) Using PCA, the most important erosion-prone significant parameters are identified. (5) Based on the PCA findings for the parameters that are most likely to cause erosion, sub-watersheds can be prioritized by using WSA technique. (5) Sub-watersheds were then ranked and organized according to priority for soil conservation planning and management using the WSA technique. In this work, PCA analysis was performed utilizing IBM-SPSS Statistics version 22 (IBM Corp, 2018).

2.1 Study area

The study area is situated in Mecca Province, in the western part of Saudi Arabia, and in the eastern part of Jeddah City (see Fig. 1). Eastern Jeddah sub-watersheds are located between 39° 10′ 00″ E and 39° 30′ 00″ E, as well as 21° 20′ 0″ N and 22° 00′ 0″ N (see Fig. 1). The sub-watersheds have a total area of 208.42 km^2 and elevations above sea level ranging from 38 to 400 m. Jeddah was severely devastated by rain in 2022. On November 24, 2022, there was severe flash flooding in the watersheds of eastern Jeddah. In just six hours, Jeddah received 179 mm of rain. There were reportedly at least two fatalities as a result of the city flooding. Subsequent to the intense flooding and soil erosion after heavy rainfall that struck Jeddah city, the National Center for Meteorology of Saudi Arabia reports that numerous homes were destroyed, and hundreds of vehicles were discarded.

2.2 Morphometric analysis

The geometry of watersheds and streams is described using morphometric analysis. It facilitates understanding of the watershed's geographic characteristics, the stream network's relief characteristics, and the drainage network's linear characteristics (Strahler, 1964). Stream ordering (u) and sub-watershed delineation are the main step in a watershed morphometric analysis. Stream ordering is the process of delineating existing streams along the watershed boundary. Horton (1945) and Strahler (1964) proposed that stream networks and watershed order be extracted from the watershed's DEM map.

The primary purpose of the morphometric parameters is to determine the morphometric elements that directly affect surface runoff and sediment loss from a watershed (Kumar et al., 2021). Morphometric parameters come in three different forms: shape (Equations viii to xi), areal (Equations iv to vii), and form linear (Equations i to iii). The mathematical formulas for the linear, areal, and shape parameters are given in Table 1. Watershed area

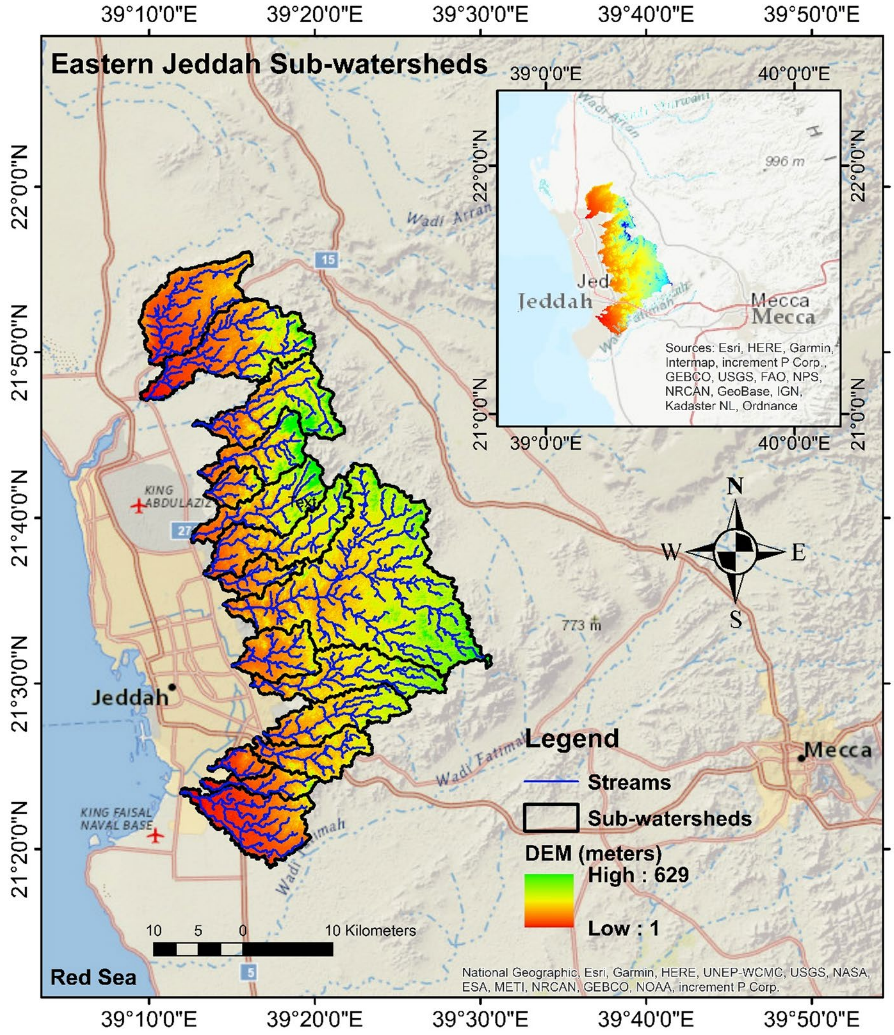

Fig. 1 Study area

(A), watershed perimeter (P), order of streams (u), stream length (L_u), mean stream length ($\bar{L}_u$), basin length (L_b), and bifurcation ratio (R_b) are the linear morphometric parameters. Drainage density (D_d), stream frequency (F_s), drainage texture (R_t), and mean surface flow length are the areal morphometric parameters (L_{om}). Shape factor (F_f), compactness coefficient (C_c), elongation ratio (R_e), and circularity ratio (R_c) make up the shape morphometric parameters (Horton, 1945; Miller, 1953; Strahler, 1964).

Schumm (1956) predicted that soil runoff would rise in proportion to the value of R_b. The proportion of the basin's length to its axial breadth is known as the form factor (F_f).

If the shape component is greater than or equal to 0.7854, the watershed is circular. Longer watershed values were indicated by lower form factor values (Rai et al., 2014).

The drainage density (D_d) is the proportion of the watershed's total surface area to the total length of all of its streams. The lowest drainage density value suggests subsurface

Table 1 Formulae used for computation of morphometric parameters of the Jeddah eastern sub-watersheds

Parameters	Parameters	Formula	References	Eq. no
Linear	Basin area (A)	Area of watershed (Km^2)		
	Basin Perimeter (P)	Perimeter of watershed (Km)		
	Stream order (u)	Hierarchical rank		
	Stream length (L_u)	Length of stream (Km)		
	Mean stream length ($\overline{L_u}$)	$\left(\overline{L_u}\right) = \frac{L_u}{N_u}$, where $(\overline{L_u})$ is the mean stream length (km). L_u is the total length of stream of order u, N_u is the total number of stream of order u	Strahler (1964)	i
	Basin length (L_b)	$L_b = 1.312 \times A^{0.568}$, (km)	Nookaratnam et al. (2005)	ii
	Bifurcation ratio (R_b)	$R_b = \frac{N_u}{N_{u+1}}$, where N_{u+1} is the number of stream segment of $(u+1)$th order	Schumm (1956)	iii
Areal	Drainage density (D_d)	$D_d = \frac{\sum L_u}{A}$, $(\mathrm{km}/\mathrm{km}^2)$, where $\sum L_u$ is the total length of stream of all orders (km)	Horton (1932)	iv
	Stream frequency (F_s)	$F_s = \frac{\sum N_u}{A}$, $(1/\mathrm{km}^2)$	Horton (1932)	v
	Drainage texture (R_t)	$R_t = \frac{\sum N_u}{P}$, $(1/\mathrm{km}^2)$	Horton (1945)	vi
	Length of overland flow (L_{om})	$L_{om} = \frac{1}{2D_d}$, (km)	Horton (1945)	vii
Shape	Form factor (F_f)	$F_f = \frac{A}{L_b^2}$	Horton (1932)	viii
	Circularity ratio (R_c)	$R_c = 4 \times \pi \times \frac{A}{P^2}$	Miller (1953)	ix
	Compactness coefficient (C_C)	$C_c = 0.2821 \times \frac{P}{A^{0.5}}$	Strahler (1964)	x
	Elongation ratio (R_e)	$R_e = 1.128 \times \frac{\sqrt{A}}{L_b}$	Schumm (1956)	xi

material that is very permeable and soil that is covered in dense shallow vegetation, whereas the greatest value shows subsurface material that is impervious and overgrown with vegetation. The density of drainage indicates the development of channels in the watershed as well as the closeness of channel spacing. Drainage density is influenced by lithology, subsoil compactness, vegetation cover, and relief (Horton, 1932). Drainage density was divided into five constitute by Smith (1950) and Horton (1945): extremely rough (>2), rough (>4), medium (4–6), fine (6–8), and very fine (>8). Stream frequency (F_s) is the sum of all stream segments for all steams divided by the watershed's area (Horton, 1932).

The ratio of a basin's surface area to a circle which perimeter matches the basin's is known as the circularity ratio (R_c) (Miller, 1953). A greater value (>0.5) denotes a more circular and uniform geologic composition. The longer basin is indicated by the lower value (0.5). The circularity ratio has a value of 1, which ranges from 0.2 to 0.8. The proportion of the basin's circumference to its equivalent circular area is known as the compactness coefficient (C_c) (Strahler, 1964). The ratio of a basin's longest length to the diameter of a circle with an equivalent area is known as the elongation ratio (R_e), according to Schumm (1956). The elongation ratio has significant hydrological implications since rainfall transported in a storm in significantly elongated basins must travel a wide range of lengths to reach the basin outlet, contrary to more circular catchments. The storm hydrograph flattens as a result of the subsequent delay until the arrival of an area of the storm flow. As a drainage basin's shape becomes closer to a circle, R_e's value approaches 1.0. The ratio fluctuates between 0.6 and 1.0 throughout a broad range of geology and climatic regimes. Zones with high relief and steep ground slopes typically have values between 0.6 and 0.8, while very low relief zones typically have values close to 1.0. The quantity of stream segments in all streams at the boundary of the watershed is known as the texture ratio (R_t), also recognized as drainage texture (Horton, 1945).

2.3 Principal component analysis (PCA)

Almost for all morphometric parameters, PCA is utilized to determine which parameters are most important. There are four fundamental stages that were taken to implement the PCA. To improve PCA's performance, the data set is normalized in the first stage. In the second stage, the covariance matrix is calculated to check for any potential correlations between the variables in the data. The third stage includes computing the PCs of the data using the eigenvalues as well as the eigenvectors of the correlation matrix. The fourth and last phase would have been the development of PCs and the function vector. When there are two PCs, the function vector—a matrix of eigenvectors—corresponds to PC1, the biggest eigenvalue (Hotelling, 1933; Hotelling, 1933; Kottegoda & Rosso, 2008; Kumar et al., 2021).

2.4 Weighted-sum approach (WSA)

Following the identification of pertinent morphometric characteristics using PCA, the related category and ultimate priority ranking of the variables were ascertained through weighted-sum analysis. Equation (1) represents the mathematical equation used in the CF computation (Aher et al., 2014; Kadam et al., 2019; Singh & Singh, 2018).

$$\mathrm{CF} = PPR_{MP} \times W_{MP} \tag{1}$$

where CF stands for compound factor, PPR is for preliminary priority rank, which can be calculated from Eq. (2), is the major morphometric parameter acquired from correlation matrix. Subwatersheds are ranked using a criterion called the Compound Factor (CF). When prioritizing subwatersheds, the subwatersheds with the lowest CF value are ranked higher, and vice versa. The CF factor is used to rank watersheds according to hydrological, topographic, and morphometric data (Aher et al., 2014). The initial priority ranking is based on the physical ideas of area and shape characteristics. For example, drainage density suggests that watersheds with high drainage densities should be given preference over those with low drainage densities. The opposite is true for shape parameters (Malik et al., 2019).

$$\mathrm{W}_{MP} = \frac{Sum\ of\ correlation\ coefficient}{Grand\ total\ of\ correlations} \tag{2}$$

The sixteen Jeddah eastern SWDs received a final priority rank in this investigation based on CF value. The CF with the least value for each SWD was assigned priority rank 1, followed by priority rank 2 for the CF with the next lowest value, and so on. Figure 2 displays the flowchart of the methods employed in the present research to rank the sub-watersheds.

3 Results and analysis

This section includes a thorough explanation of the delineation of streams and sub-watersheds, morphometric parameters, the use of the PCA method to identify key, erosion-prone morphometric parameters in order to maximize the sub-watersheds that are most susceptible to land management strategies, and the use of the WSA for priotrization of sub-watersheds. Figures 2 and 3 show the delineated stream order and sub-watershed order, respectively.

3.1 Delineation of streams and sub-watersheds

This work used the ArcGIS (10.4) spatial analyst feature and the DEM map to determine streams orders and sub-watersheds. In Table 2 and Figs. 2 and 3, the characteristics of streams and sub-watersheds are described in detail.

3.2 Morphometric analysis

To evaluate the features of the drainage basins, a morphometric analysis was conducted using GIS for 16 sub-watersheds in eastern Jeddah. In this work, sixteen Sub-watersheds' linear, areal, and form morphometric parameters were examined using the ArcGIS environment (see Fig. 4). Tables 2 and 3 present their quantitative values, respectively.

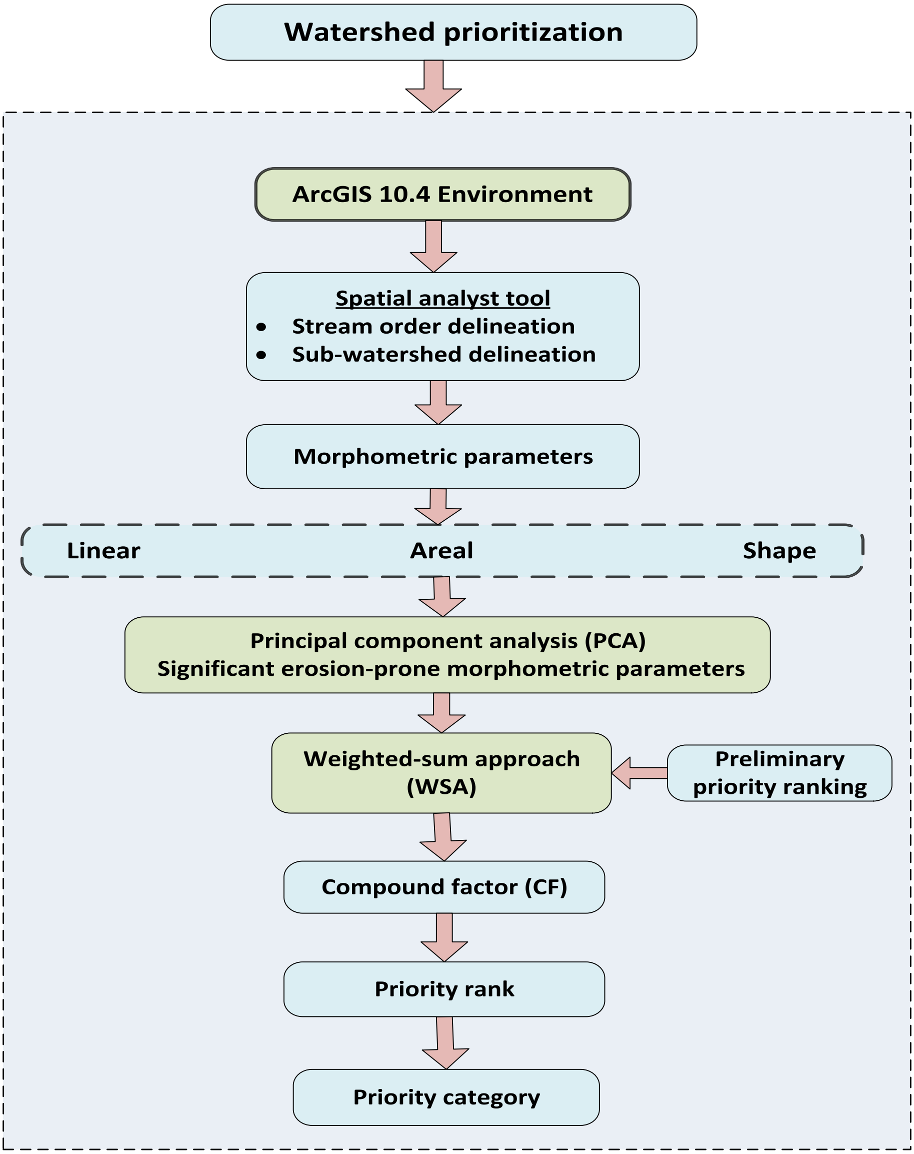

Fig. 2 Flow chart of eastern Jeddah. Sub-watershed prioritization

3.3 Linear parameters

The stream order (u) categorization plays a key role in establishing the size and scope of the basin. In the study area, the third order SWDs are SWD-1, SWD-3, SWD-4, SWD-5, SWD-7, SWD-8, SWD-11, SWD-13, SWD-14, and SWD-15, which include areas of 76.021 ha, 70.260 ha, 41.884 ha, 17.524 ha, 66.181 ha, 20.548 ha, 67.301 ha, 39.29 ha, 13.317 ha, and 21.720 ha, respectively.

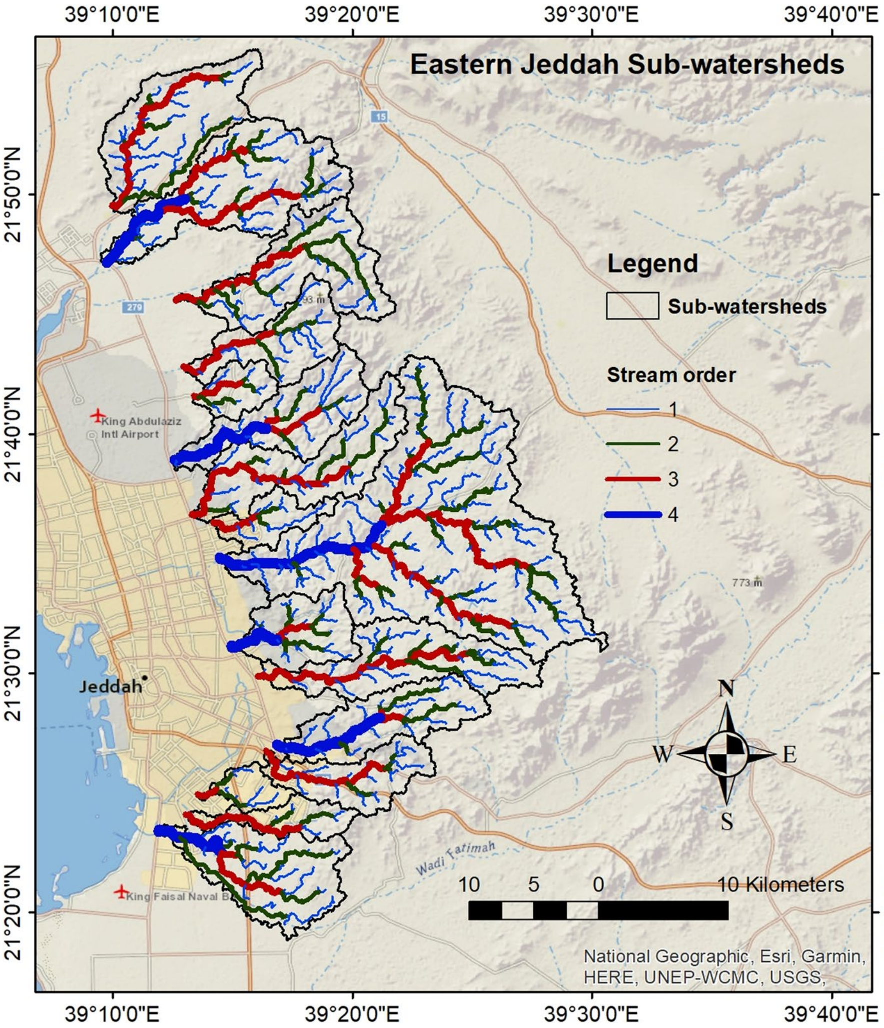

Fig. 3 Stream order of the sixteen sub-watersheds

Conversely, SWD-2, SWD-6, SWD-9, SWD-10, SWD-12, and SWD-16 are fourth order and include, the respectively, 91.98 ha, 54.548 ha, 278.127 ha, 38.247 ha, 52.695 ha, and 66.26 ha (Table 3).

The bifurcation ratio (R_b) is a valuable indicator of flooding susceptibility; the greater the ratio, the larger the risk of flooding. The ratio of the stream values in a particular order to the stream values in the order below it is known as R_b, according to Horton (1945). In this work, the bifurcation ratio ranges from 2.75 for SWD-14 to 6.25 for SWD-1 (Table 4).

Table 2 Linear morphometric parameters for 16 sub-watersheds in the eastern part of Jeddah

Characteristics variables

Sub-watershed (SWD)	A (Km^2)	P (Km)	Streams order (u)				N$_u$	L_u (km)	($\overline{L_u}$) (Km)	L_b (km)
			1	2	3	4				
SWD-1	76.021	52.971	36	8	1	0	45	78.944	1.754	15.357
SWD-2	91.980	66.210	40	11	2	1	54	99.732	1.847	17.112
SWD-3	70.260	60.688	27	6	1	0	34	70.718	2.080	14.685
SWD-4	41.884	42.077	16	6	1	0	23	40.103	1.744	10.946
SWD-5	17.524	21.051	8	3	1	0	12	16.713	1.393	6.673
SWD-6	54.548	49.801	24	5	2	1	32	53.388	1.668	12.718
SWD-7	66.181	62.740	29	6	1	0	36	60.864	1.691	14.194
SWD-8	20.548	32.054	8	2	1	0	11	20.205	1.837	7.304
SWD-9	278.127	121.439	123	23	4	1	151	274.124	1.815	32.082
SWD-10	38.247	32.426	23	5	2	1	31	35.937	1.159	10.396
SWD-11	67.301	64.544	24	6	1	0	31	72.692	2.345	14.330
SWD-12	52.695	48.507	22	4	2	1	29	51.575	1.778	12.471
SWD-13	39.290	42.924	16	3	1	0	20	38.155	1.908	10.556
SWD-14	13.317	22.548	6	2	1	0	9	15.017	1.669	5.709
SWD-15	21.720	36.735	7	2	1	0	10	22.092	2.209	7.540
SWD-16	66.260	54.877	23	5	2	1	31	79.517	2.565	14.204

3.4 Areal parameters

According to Horton (1945), drainage density (D$_d$) is the ratio of the watershed's entire stream length—all orders combined—to its drainage area. This ratio is dependent on the relief, vegetation types, and subsurface material permeability. In low relief, heavily vegetated terrain, and extremely permeable underlying earth situations, less D$_d$ is usually observed.

All sub-watersheds have drainage densities (D$_d$) ranging from 0.92 km/km^2 (SWD-7) to 1.20 km/km^2 (SWD-16). On the other hand, minimal vegetation, high relief, and a well-established, efficient drainage network are indicated by a higher SWD-16 drainage density score. The low drainage density result for SWD-7 indicates a relatively permeable subsurface beneath a vegetative cover with limited relief.

The ratio of streams to catchment area is known as stream frequency (F$_s$). The stream frequency (F$_s$) of the sub-watershed ranges from 0.46 km^2 (SWD-15) to 0.811 km^2 (SWD-10). Significant runoff is indicated by a high stream frequency number, whereas little to no runoff is indicated by a low one. The drainage texture ratio (R$_t$) was computed, according to Horton (1945), by divided the total number of segment streams (N$_u$) for all stream orders by the watershed's perimeter (P).

Horton (1945) asserts that the infiltration capability of the basin is the only major factor that determines its drainage texture value. The values of drainage texture (R$_t$) vary from 1.243 km^{-1} (SWD-9) to 0.272 km^{-1} (SWD-15). Consequently, the drainage textures of all SWDs are fairly rough.

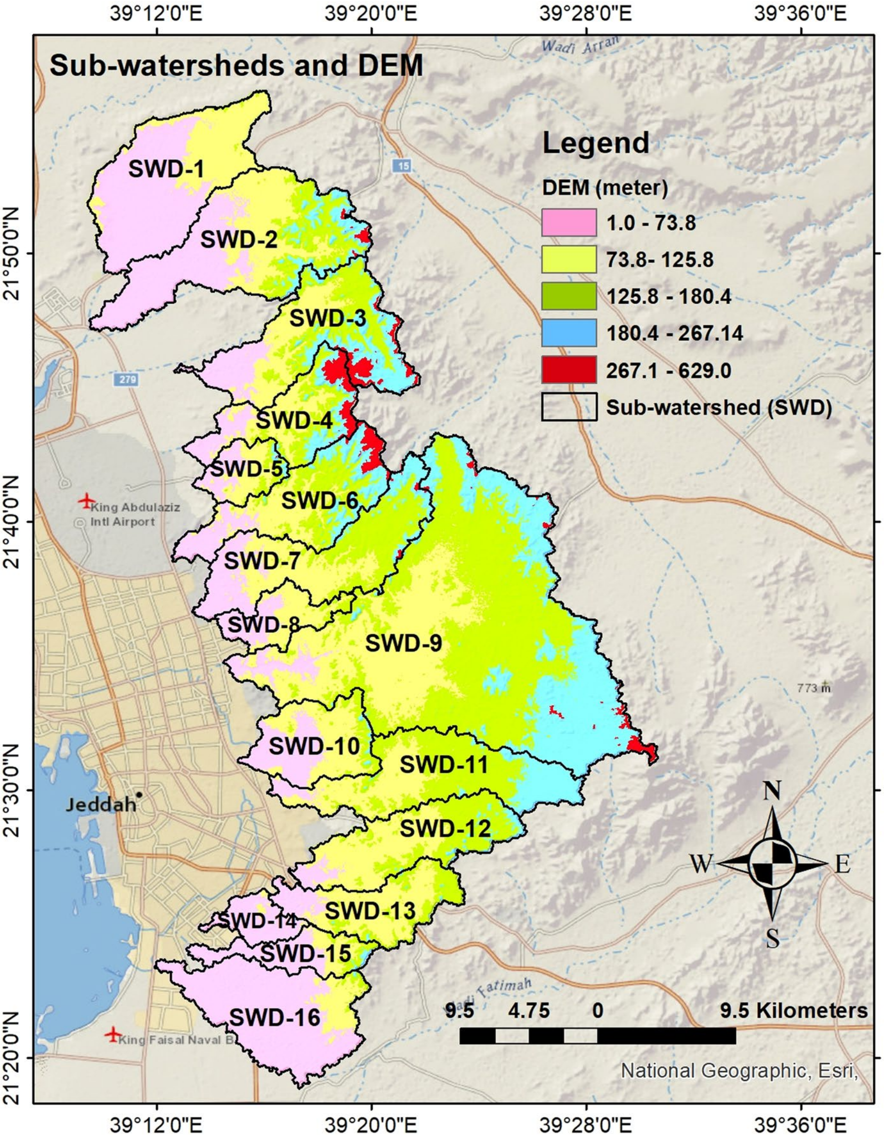

Fig. 4 The sixteen Jeddah eastern sub-watersheds

The entire quantity of water that flows across the ground surface before condensing into distinct stream courses is known as the length of water flow (L_{om}). The L_{om} describes the flow of precipitation that crosses the surface of the ground and creates stream channels, which are often determined by the length of the slope and the characteristics of the land cover. The physiographic and hydrologic developments of the drainage basin are significantly influenced by L_{om}, an independent variable. The L_{om} of the SWDs ranges from 0.417 km (SWD-16) to 0.544 km (SWD-7). A faster runoff process is indicated by a shorter L_{om} for SWD-16, and vice versa (Table 4).

Table 3 Linear, areal, and shape parameters of the study area

Sub-watershed (SWD)	Sub-watershed morphometric variables								
	Linear	Areal				Shape			
	R_b	D_d (km/km^2)	F_s (km^{-2})	R_t (km^{-1})	L_{om} (km)	F_f	R_c	C_c	R_e
SWD-1	6.250	1.038	0.592	0.850	0.481	0.322	0.341	1.714	0.640
SWD-2	3.712	1.084	0.587	0.816	0.461	0.314	0.264	1.948	0.632
SWD-3	5.250	1.007	0.484	0.560	0.497	0.326	0.240	2.042	0.644
SWD-4	4.333	0.957	0.549	0.547	0.522	0.350	0.297	1.834	0.667
SWD-5	2.833	0.954	0.685	0.570	0.524	0.394	0.497	1.419	0.708
SWD-6	3.100	0.979	0.587	0.643	0.511	0.337	0.276	1.902	0.655
SWD-7	5.417	0.920	0.544	0.574	0.544	0.328	0.211	2.176	0.646
SWD-8	3.000	0.983	0.535	0.343	0.508	0.385	0.251	1.995	0.700
SWD-9	5.033	0.986	0.543	1.243	0.507	0.270	0.237	2.054	0.586
SWD-10	3.033	0.940	0.811	0.956	0.532	0.354	0.457	1.479	0.671
SWD-11	5.000	1.080	0.461	0.480	0.463	0.328	0.203	2.219	0.646
SWD-12	3.167	0.979	0.550	0.598	0.511	0.339	0.282	1.885	0.657
SWD-13	4.167	0.971	0.509	0.466	0.515	0.353	0.268	1.932	0.670
SWD-14	2.500	1.128	0.676	0.399	0.443	0.409	0.329	1.743	0.721
SWD-15	2.750	1.017	0.460	0.272	0.492	0.382	0.202	2.223	0.697
SWD-16	3.033	1.200	0.468	0.565	0.417	0.328	0.277	1.902	0.646

3.5 Shape parameters

According to Horton (1932), the form factor, which represents the basin's shape, is defined as the basin's area (A) divided by its length (L_b). A bigger form factor number suggests the basin's inclination to be circular, whereas a smaller form factor value shows the basin's more elongated shape. The watershed was comparatively elongated, as indicated by the lesser value of F_f, and will have a flatter peak flow over a prolonged period of time. It is simpler to control the peak flows from these SWDs than from the circular SWDs. According to Table 3, the form factor (F_f) denotes an extended shape with a smaller peak flow over a longer time span. It ranges from 0.27 (SWD-9) to 0.409 (SWD-14).

The circulation ratio (R_c) gets closer to unity as the basin shape gets closer to a circle (Miller, 1953). The R_c values in this work (Table 5) range from 0.202 (SWD-15) to 0.497 (SWD-5), which is less than unity and nearly elongates the form of the SWDs. The combination of diverse geological circumstances and a delay in topographical development stages accounts for the highest value of R_c (0.497) for SWD-5.

The compactness constant (C_c) is expressed as a proportion of the basin perimeter to the circle perimeter to the same watershed area (Horton, 1945). It is directly correlated with the evaluation parameters for erosion risk. Higher values of C_c indicate greater vulnerability and the need for conservation measures to be implemented, whilst lower levels indicate reduced vulnerability to risk factors. The values of the compactness coefficient (C_c) range from 1.419 (SWD-5) to 2.223 (SWD-15). Table 3 shows that all SWDs have a steep ground slope and significant relief based on the elongation ratio (R_e), which varies from 0.586 (SWD-9) to 0.721 (SWD-14).

Table 4 correlation matrix between linear, areal, and shape morphometric variables of sixteen sub-watersheds

Morphometric parameters	R_b	D_d	F_s	R_t	L_{om}	F_f	R_c	C_c	R_e
R_b	1.000	−0.165	−0.314	0.374	0.150	−0.663***	−0.327	0.325	−0.659***
D_d	−0.165	1.000	−0.272	−0.151	−0.997	−0.018	−0.188	0.122	−0.022
F_s	−0.314	−0.272	1.000	0.377	0.286	0.310	0.846**	−0.837**	0.304
R_t	0.374	−0.151	0.377	1.000	0.152	−0.722***	0.241	−0.262	−0.733***
L_{om}	0.150	−0.997*	0.286	0.152	1.000	0.022	0.206	−0.139	0.026
F_f	−0.663***	−0.018	0.310	−0.722***	0.022	1.000	0.389	−0.356	0.920*
R_c	−0.327	−0.188	0.846**	0.241	0.206	0.389	1.000	−0.906*	0.387
C_c	0.325	0.122	−0.837	−0.262	−0.139	−0.356	−0.976*	1.000	−0.354
R_e	−0.659***	−0.022	0.304	−0.733	0.026	0.999*	0.387	−0.354	1.000

Table 5 Total variance explained for Jeddah eastern sub-watersheds

Morphometric variables	Initial eigenvalues			Extraction sums of squared loadings			Rotation sums of squared loadings		
	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %
R_b	3.788	42.093	42.093	3.788	42.093	42.093	3.132	34.803	34.803
D_d	2.763	30.695	72.788	2.763	30.695	72.788	3.100	34.441	69.244
F_s	1.733	19.255	92.043	1.733	19.255	92.043	2.052	22.799	92.043
R_t	0.469	5.212	97.255						
L_{om}	0.188	2.088	99.342						
F_f	0.037	0.407	99.750						
R_c	0.020	0.223	99.973						
C_c	0.002	0.026	99.998						
R_e	0.000	0.002	100.000						

3.6 Principal component analysis of morphometric variables

The initially unrotated factor loading (FL) matrix, rotating FL matrix, and correlation matrix were obtained using orthogonal transformation and the PCA (Arefin et al., 2020). Table 4 displays the findings of the correlation analysis of all morphometric characteristics. Table 4 demonstrates that $r > 0.9$ between D_d and L_{om}; between R_c and C_c, and between R_e and F_f have substantial correlations ($r > 0.9$). There is a significant connection between R_c and F_s as well as between C_c and F_s ($r > 0.75$). There is a moderate relationship ($r > 0.60$) between R_b and F_f, R_b and R_e, R_t and F_f, F_f and Re, R_e and R_b, and R_e and R_t. Classification of the parameters into significant components based on relative relevance is difficult because the majority of the values included in the matrix of correlation have weak correlations. PCA was performed on the resulting inter-correlation matrix to arrange the most significant erosion-prone morphological variables into main components that characterize the information provided.

Table 5 showed that the first three components, each of which has an eigenvalue larger than 1, together account for around 92.043% of the eastern Jeddah sub-watersheds overall variation. Partitioning the variables at this point and assigning physical value would be too complex. Principal component analysis is used to create the basic factor loading (FL) of matrix (unrotated FL matrix) for each morphometric parameter in order to obtain the significant morphometric parameters.

Table 6 shows the initial unrotated FL matrix for all morphometric parameters. A weak relationship with R_b was found, along with significant correlations with F_f, R_c, and R_e for the first component (PC-1). The second part (PC-2) exhibits a strong correlation with R_t and L_{om}. The PC-3's third component has a strong correlation with D_d. The analysis revealed that some elements (PC-1, PC-2, and PC-3) had a moderate to strong association with the morphometric parameters, however all three components (PC-1, PC-2, and PC-3) lack any significant correlation with other morphometric parameters. Thus, it is challenging to obtain a necessary physical component in this scenario.

Furthermore, it's critical to keep in mind that a high PC loading value denotes a strong correlation between the component and the specific morphometric measure. The initial unrotated FL matrix requires to be rotated in order to increase correlation. Table 7 displays the rotated FL matrix of the original unrotated FL matrix. The first component, also known

Table 6 Unrotated factor-loading (FL) matrix of morphometric parameters

Morphometric variables	Principal component		
	1	2	3
R_b	−0.670	0.419	−0.116
D_d	−0.198	−0.595	0.774**
F_s	0.750	0.523	0.235
R_t	−0.247	0.846**	0.407
L_{om}	0.212	0.600***	−0.766
F_f	0.817**	−0.509	−0.217
R_c	0.819**	0.431	0.289
C_c	−0.793	−0.419	−0.362
R_e	0.815**	−0.512	−0.225

as the stage-form component (PC-1), has strong correlation to the other components F_f and R_e. The second component, PC-2, exhibits a high correlation with F_s, R_c, and C_c (Table 7).

The third part (PC-3) could be referred to as the organization-process component because of its substantial association with L_{om} and D_d and no correlation with other parameters. The three most important morphometric parameters, according to an analysis of the rotated FL matrix, are the elongation ratio (R_e), circulation ratio (R_c), and mean length of overland flow (L_{om}). These morphometric parameters are then used for WSA and SWD prioritizing. R_e received the highest correlation of 0.961 in the first component, R_c received the highest correlation of 0.949, and L_{om} received the highest correlation of 0.99 in the third component (see Table 7).

3.7 Assign preliminary priority rank to the SWDs

Soil erodibility is closely related to the linear and areal parameters; a greater value of these parameters denotes a potential for increased erodibility. The linear and areal parameter value for each sub-watershed was given rank 1 (highest priority), then rank 2 (second-highest priority), and so on. The link between the form morphometric parameters and soil erodibility is inverse; a lower value denotes a greater potential for erodibility (see Table 8). According to Thakkar and Dhiman (2007), the form parameter with the smallest value across all SWDs was assigned rank 1. The next lowest value was given rank 2, and on and so forth. In the event that the value of any morphometric parameter between two sub-watersheds was similar, a SWD was given the same rank (Kandpal et al., 2018; Malik et al., 2019).

3.8 Weighted-sum analysis of significant morphometric variables

Three important morphometric parameters (L_{om}, R_c and R_e) were taken into account when ranking sixteen of Eastern Jeddah sub-watersheds. Table 8 shows the results of the cross-correlation of the three significant variables that were acquired from the PCA analysis. The sixteen SWD's preliminary priority rating is displayed in Table 9. By dividing the total

Table 7 Rotated factor-loading (FL) matrix of morphometric parameters

Morphometric variables	Principal component		
	1	2	3
R_b	−0.699	−0.321	0.213
D_d	0.043	−0.108	−0.987
F_s	0.076	0.923*	0.183
R_t	−0.862	0.443	0.055
L_{om}	−0.039	0.125	0.990*
F_f	0.958*	0.232	0.044
R_c	0.170	0.949*	0.100
C_c	−0.139	−0.947	−0.029
R_e	0.961*	0.226	0.048

number of correlations by the sum of the correlation coefficients for each variable, the weights of each morphometric parameter were determined (Table 10).

3.9 Prioritization of SWD using PCA-WSA

The sub-watershed with the least CF value obtained rank 1 in its final priority ranking, then followed by the next lowest sub-watershed with rank 2, and so forth for the other sixteen sub-watersheds (see Table 2 and Fig. 5). The SWD-9 identified PR as 1, the SWD-4 identified PR as 2, the SWD-3 identified PR as 3, the SWD-2 identified PR as 4, the SWD-7 identified PR as 5, the SWD-13 identified PR as 6, the SWD-14 identified PR as 7, the SWD-6 identified PR as 8, and the SWD-1 identified PR as 9. This information is clearly displayed in Table 10. SWD-8 gave PR a rating of 10, SWD-12 gave PR a rating of 12, SWD-10 gave PR a rating of 13, SWD-4 gave PR a rating of 14, SWD-14 gave PR a rating of 15, and SWD-5 gave PR a rating of 16 (see Fig. 5). Table 11 displays the sixteen SWDs in eastern Jeddah's priority group based on CF value. The five-priority category has been used to group the sixteen SWDs: Very high (5.33–6.95), high (6.95–9.75), medium (9.75–10.62), low (10.62–11.33), and extremely low > 11.33 are the four categories.

It is classified as very high for the sub-watersheds SWD-9, SWD-11, SWD-3, SWD-2, and SWD-7, high for SWD-15, SWD-16, SWD-6, SWD-1, medium for SWD-8, SWD-13, and SWD-12, low for SWD-4, and very low for SWD-10, SWD-14, and SWD-5. The final priority map for the sixteen SWDs is illustrated in Fig. 5, which shows the percentage of the area that falls within each of the following categories: very high (56.48%), high (21.51%), medium (11.07%), low (4.12%), and very low (6.80%).

4 Summary and conclusions

Watershed prioritizing is the process of ranking various watersheds so that restoration through soil and water conservation measures will be prioritized for them. This work examined the effectiveness of a hybrid strategy, principal component analysis and weighted-sum approach (PCA-WSA), in an attempt to prioritize the eastern Jeddah sub-watersheds. Utilizing a rotated FL matrix and PCA according to correlations, the key morphometric characteristics in each of the 16 sub-watersheds which undergone morphometric analysis were determined in order to simplify the data. The 16 SWDs were given priority rank and category based on CF value after PCA, which was followed by weighted-sum analysis of relevant morphometric parameters for CF valve computation. The PCA successfully reduces nine key selected erosion-prone morphometric parameters to three significant parameters (R_e, R_c, L_{om}) in order to maximize the sub-watersheds that are most vulnerable to land management strategies.

Table 8 Cross correlation matrix of the most significant morphometric parameters obtained from PCA (L_{om}, R_c, and R_e)

	L_{om}	R_c	R_e
L_{om}	1.000	0.206	0.026
R_c	0.206	1.000	0.387
R_e	0.026	0.387	1.000
Sum of correlation	1.233	1.593	1.413
Grand total	4.239	4.239	4.239
Weight	0.291	0.376	0.333

Table 9 Preliminary ranking of 16 SWDs based on PCA-derived relevant morphometric characteristics

Sub-watershed	L_{om}	R_c	R_e
SWD-1	12	14	3
SWD-2	14	7	2
SWD-3	10	5	4
SWD-4	4	12	10
SWD-5	3	16	15
SWD-6	6	9	8
SWD-7	1	3	7
SWD-8	8	6	14
SWD-9	9	4	1
SWD-10	2	15	12
SWD-11	13	2	5
SWD-12	7	11	9
SWD-13	5	8	11
SWD-14	15	13	16
SWD-15	11	1	13
SWD-16	16	10	6

Table 10 Final priority rank of 16 SWDs based on the CF value

Sub-watershed	Compound factor	Prioritized ranks
SWD-1	9.75	9
SWD-2	6.79	4
SWD-3	6.7	3
SWD-4	11.33	14
SWD-5	14.5	16
SWD-6	9.54	8
SWD-7	6.95	5
SWD-8	10.41	11
SWD-9	5.33	1
SWD-10	13.13	13
SWD-11	5.91	2
SWD-12	10.62	12
SWD-13	10.16	10
SWD-14	13.71	15
SWD-15	8.2	6
SWD-16	9.25	7

Watershed expansion and maintenance over the long future depend on giving priority to SWD. In this work, morphometric parameter data has been investigated using GIS. The PCA-WSA combination was effectively used to prioritize sixteen watersheds of eastern Jeddah. The sub-watersheds, according to the study.

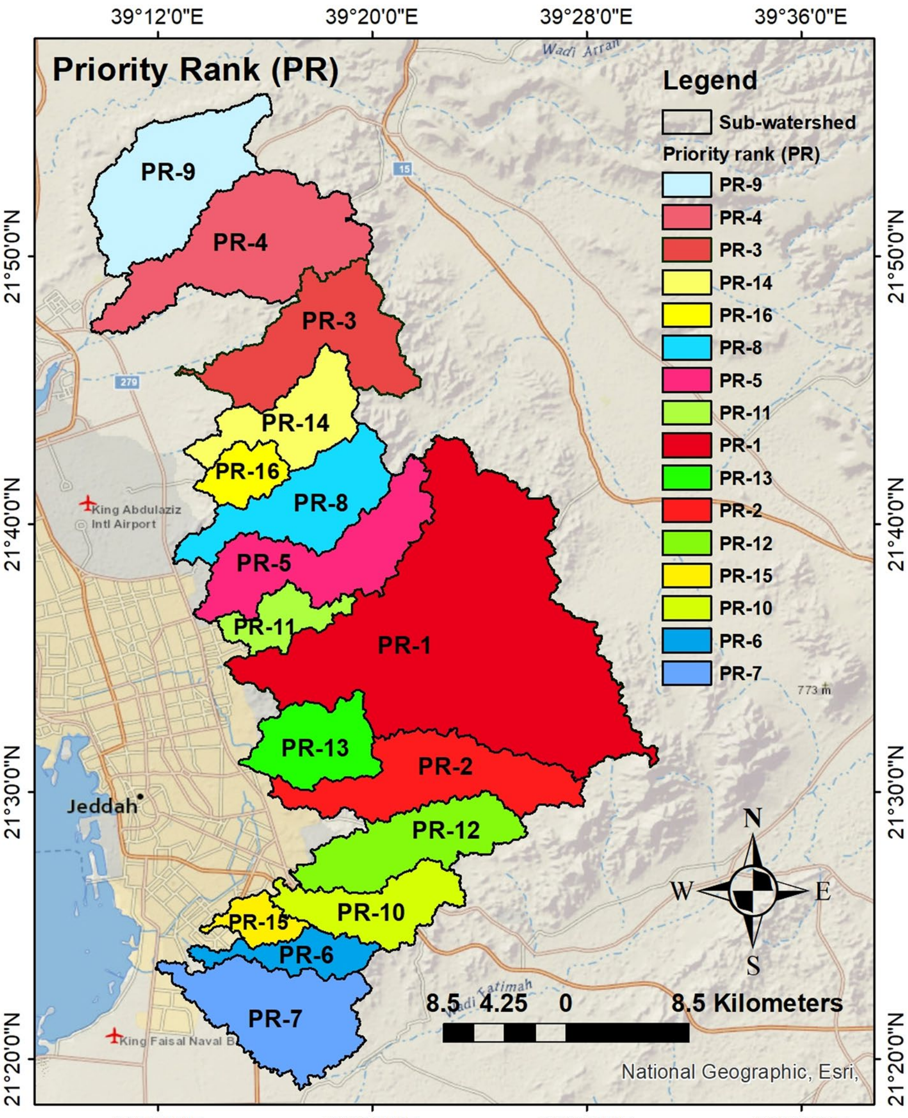

Fig. 5 Final priorty rank of the 16 sub-watersheds

Table 11 Priority category of the sixteen sub-watersheds based on the Compound Factor (CF)

Sr. no	Priority level	Priority category	Sub-watershed	Percentage of area
1	5.33 to ≤ 6.95	Very high	SWD-9, SWD-11, SWD-3, SWD-2, SWD-7	56.48
2	6.95 ≤ 9.75	High	SWD-15, SWD-16, SWD-6, SWD-1	21.51
3	9.75 ≤ 10.62	Medium	SWD-8, SWD-13, SWD-12	11.07
4	10.62 ≤ 11.33	Low	SWD-4	4.12
5	>11.33	Very low	SWD-10, SWD-14, SWD-5	6.8

The extremely high category includes SWD-9, SWD-11, SWD-3, SWD-2, and SWD-7, while the very high susceptibility or susceptible zones category includes SWD-15, SWD-16, SWD-6, and SWD-1. The work helps decision-makers identify priority SW that demand the quick deployment of efficient soil and water conservation methods in the examined region. The terrible floods that occurred in 2009 and 2012, which took several lives and destroyed numerous homes, were primarily caused by sub-watersheds 9 and 11 (SWD-9 and SWD-11). According to the PCA-WSA, SWD-9 and SWD-11 are the most susceptible to flooding. This demonstrates that the adoption of PCA-WSA in all sub-watersheds that experience flash floods has a great deal of opportunity. In order to determine vulnerability or risk assessment prioritized areas for informed decision making in the research region, the suggested strategy for prioritizing watersheds therefore offers a useful approach.

PCA-WSA is one of the useful and significant solutions since geo-informatics and statistical techniques are combined in a single framework, especially when compared to the information prioritization alternatives. Additionally, in contrast to conventional or traditional watershed prioritization procedures, the proposed hybrid methodology produces dynamic, efficient, and long-lasting results by sophisticatedly accounting for the relative relevance of numerous morphometric parameters. The best miniature planning and management strategies can be developed, implemented, and adjusted with the use of this hybrid (PCA-WSA) modeling in order to preserve existing natural resources and assist managers and policymakers in making decisions more effectively in a region where data are few. Hydrologists and geomorphologists may find this research to be a useful resource in creating and implementing comprehensive plans for managing watersheds in risky areas. The morphometric analysis will provide crucial details on the most susceptible sub-watershed, where there is a significant likelihood of flooding and soil erosion. The results of the study also provide a useful approach for prioritizing high-priority areas in order to design initiatives that prevent soil erosion and encourage soil conservation. Both ecological and physical solutions, such check dams, planting multifunctional tree species, and building stone and vegetative barriers, may be required, based on the correct location and the requirements for design.

Additionally, the study helps to protect the natural assets that are currently available and supports policymakers' and watershed managers' decision-making in a field with limited data. This data can be utilized to develop, implement, and adjust the best SWD-level planning and management techniques. It is imperative that decision makers strategically distribute investments to sub-watersheds that are both economically and technically viable. Lastly, it must be monitored and assessed in a way that is socially, economically, and environmentally acceptable.

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